Predictive Models for Integrated Manufacturing and Structural Performance of Carbon Fiber Composites for Automotive Applications

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General Motors

2019 Annual Merit Review

June 11, 2019

Project ID: MAT117

Overview

Timeline

- Project Start Date: May 1, 2015
- Project End Date: December 18, 2019
- Percent Complete: 85 %

Budget

- Total project funding
  - DOE Share: $6,000,00
  - Contractor Share: $2,571,253
- Funding for FY17 :
  - DOE share: $1,177,715
  - Contractor share: $504,735
- Funding for FY18:
  - DOE Share: $1,296,961
    Contractor Share: $555,840

Barriers and Technical Targets

Barriers addressed*

A. ***Manufacturing Technology:*** Stochastic manufacturing simulation tools to predict the outcome within 15% of experimental results to reduce cost.

B. ***Performance Technology:*** Stochastic structural performance simulation to predict the outcome within 15% of experimental results to optimize design.

C. ***Integrated Technology:*** Integrative manufacturing and structural performance simulation tool that can be used in upfront design to deliver the required assembly performance without any trial and error.

*2017 U.S. DRIVE Roadmap Report, section 4

Participants

General Motors
Continental Structural Plastics (CSP)
ESI Group, NA
Altair
University of Southern California

Relevance

Predictive Integrated Modeling Tools

- Primary deliverable: An ICME model capable of predicting stochastic manufacturing and structural performance of carbon fiber (CF) composite~~s~~ structures.
  - Reduce the cost of manufacturing CF reinforced automotive components by eliminating trial and error through improved manufacturing simulations.
  - Design, optimize and validate a CF automotive structure in a virtual design space through improved performance modeling.
  - Reduce the lead time and costs to design and implement large scale structural automotive composites.
  - Enable the usage of CF composites for significant light-weighting of automobiles and thus improve fuel economy, and lower emissions, which will reduce greenhouse gas emissions.

Cost Barrier

- Will demonstrate the ability to manufacture the automotive CF composites at no more than <u>**$4.32** cost per pound weight saved for body and **$4.27** for chassis areas to address the DOE 2030 targets.</u>

Performance Barrier

- Will demonstrate the viability of CF composites to meet vehicle performance requirements while reducing vehicle assembly weight **(35% lighter for body and 25% for chassis)** compared to a current steel design.

Relevance

Steps in implementing CF in automobiles

Current

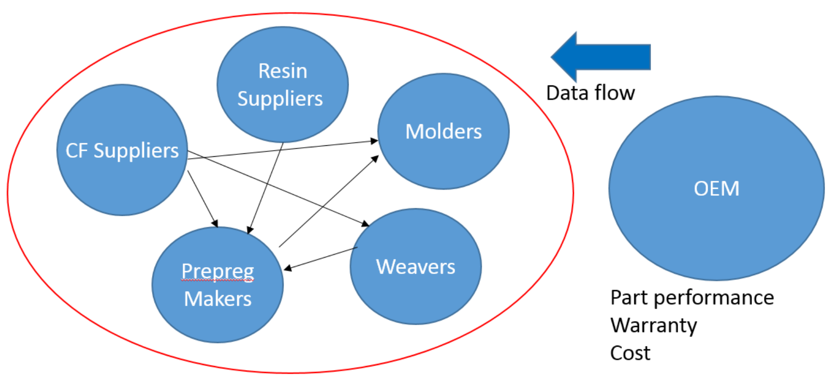
- Design.
- Selection of manufacturing process.
- Manufacturing feasibility.
- Prototype build and learn.
- Modify design and manufacturing process, if needed.
- Improve prototype build and make part.
- Extrapolate to high volume manufacturing.
- Build the part, iterate to get good quality.
- Evaluate the performance and compare with requirements.
- If failure occurs, redesign the part.

Future

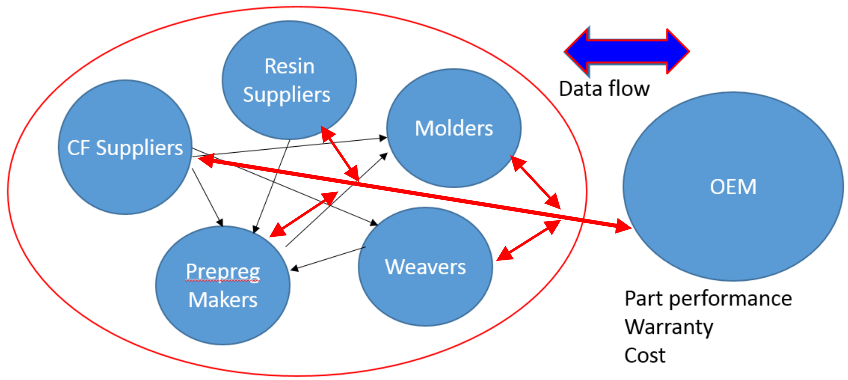
- Design.
- Virtual manufacturing simulation and improve the design for optimizing the cost.
- Include manufacturing outcome in performance simulation and further optimize the design to meet the requirements.
- Build tools, manufacture parts and check the performance

Work flow between OEM and Suppliers

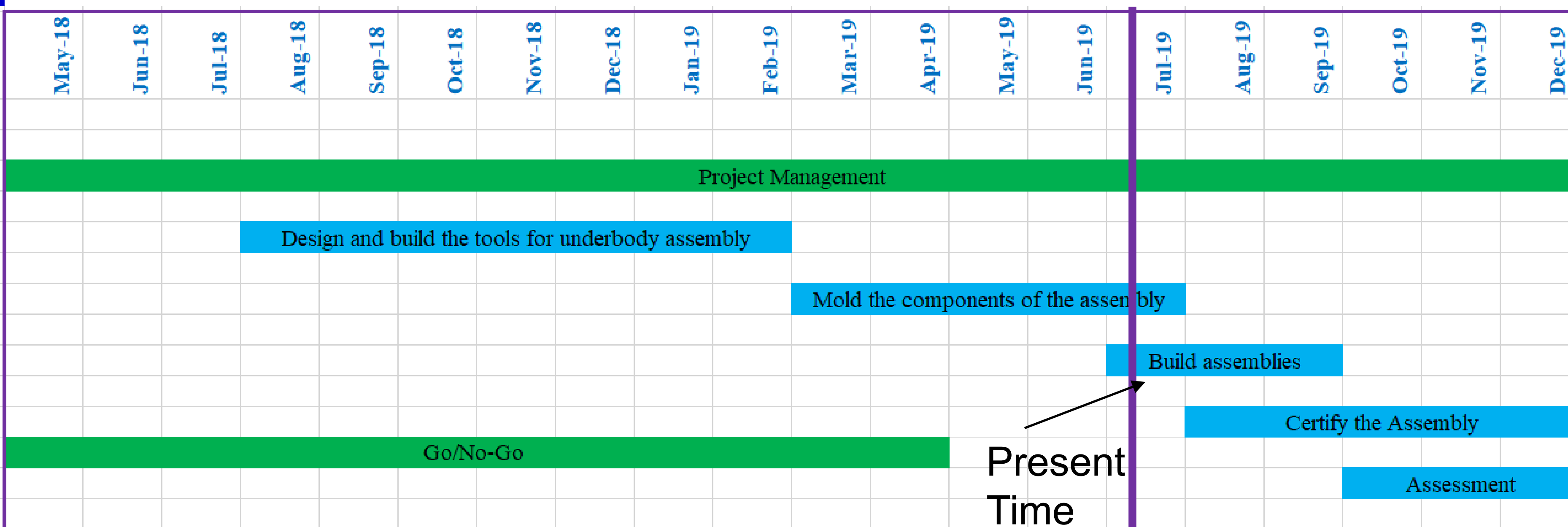
Current



Future



Milestones



All milestones for year 2019 are complete.

Go/No-Go decision was also complete.

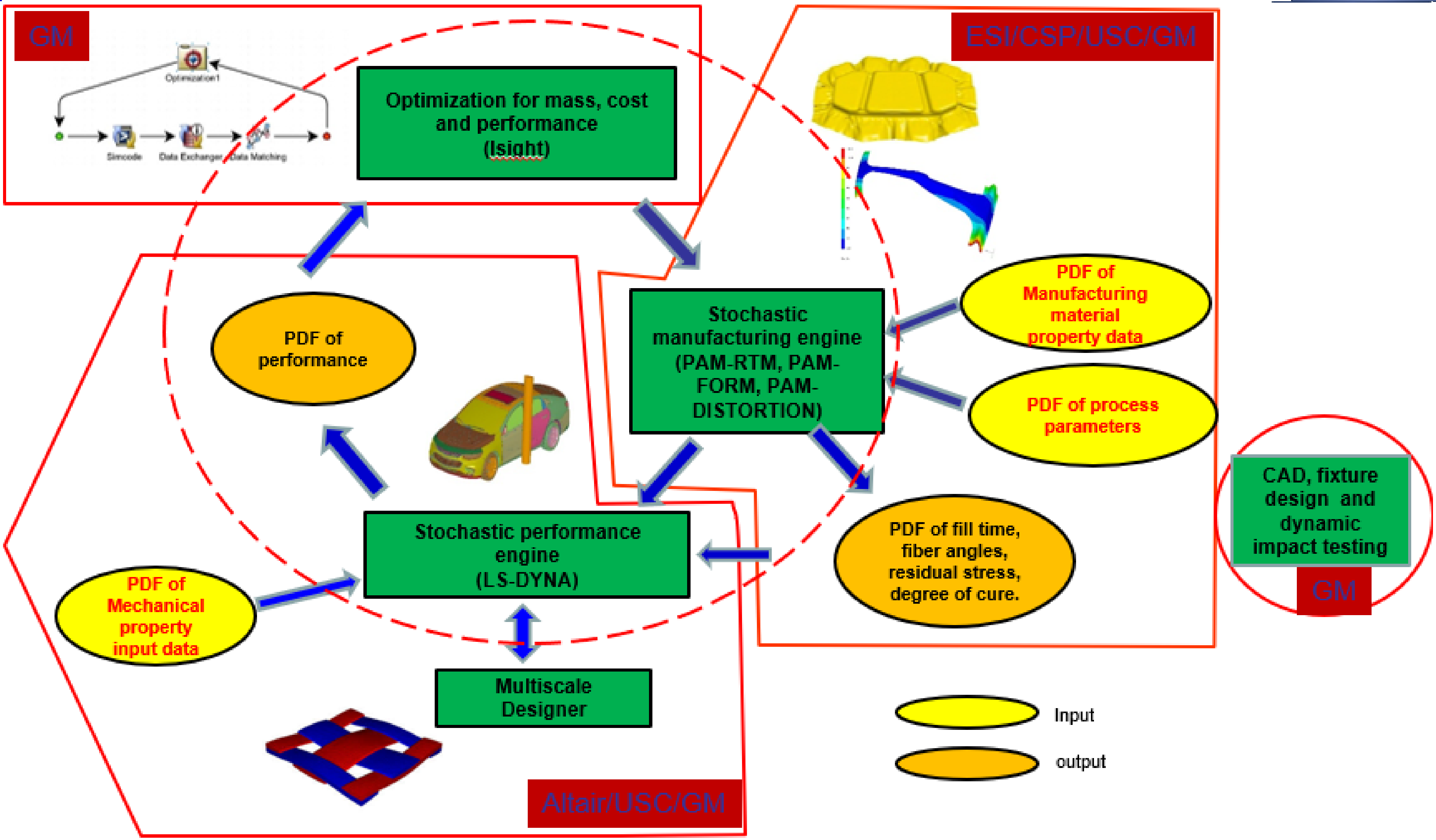
As tools arrived late, we requested no-cost extension till Dec 2019

Approach/Strategy

- An ICME approach to develop
  - computational methodologies and tools for predicting stochastic manufacturing.
  - computational methodologies and tools for predicting stochastic performance.
  - Integrated tools to predict the performance of an assembly.
- A team comprised of an automobile OEM, a Tier 1 composite system supplier and molder, software simulation companies in the areas of composite manufacturing and performance prediction, and a DOE funded SciDAC institute for uncertainty quantification.
- **Composite System Supplier**: Responsible for selecting materials and manufacturing processes for high volume manufacturing, providing plaques and coupons for generating the data required for model calibration and validation.
- **Software Companies:** Responsible for the development of predictive tools for manufacturing and structural performance
- **Stochastic Modeling Research Group:** Responsible for developing stochastic models for both manufacturing and structural performance
- **OEM:** Responsible for developing and conducting experiments for model confirmation, integrating the manufacturing and structural performance tools, demonstrating the technology by design, optimizing, building and testing a carbon fiber automotive assembly as well as validating the developed models by comparing the predictions with experimental results.

Approach/Strategy

Developed a process flow of tool development



Accomplishments

FY 18 Accomplishments

Manufacturing simulation tool development and validation

- 100% virtual design of tools to build four major components of the underbody assembly using HP-RTM. Developed optimum process conditions for the tool design.

Structural simulation tool development and validation

- Non-orthogonal weave modeling and correlation
- Engineer the structural design of underbody components for crashworthiness in side pole impact.

Cost models for the underbody assembly

- Novel cost models based on plant level modeling

Design and build tools

- Three large tools to mold four large components were built based on 100% virtual simulations.

Fabricate the components

- Fabrication started for the reinforcement part of the underbody assembly

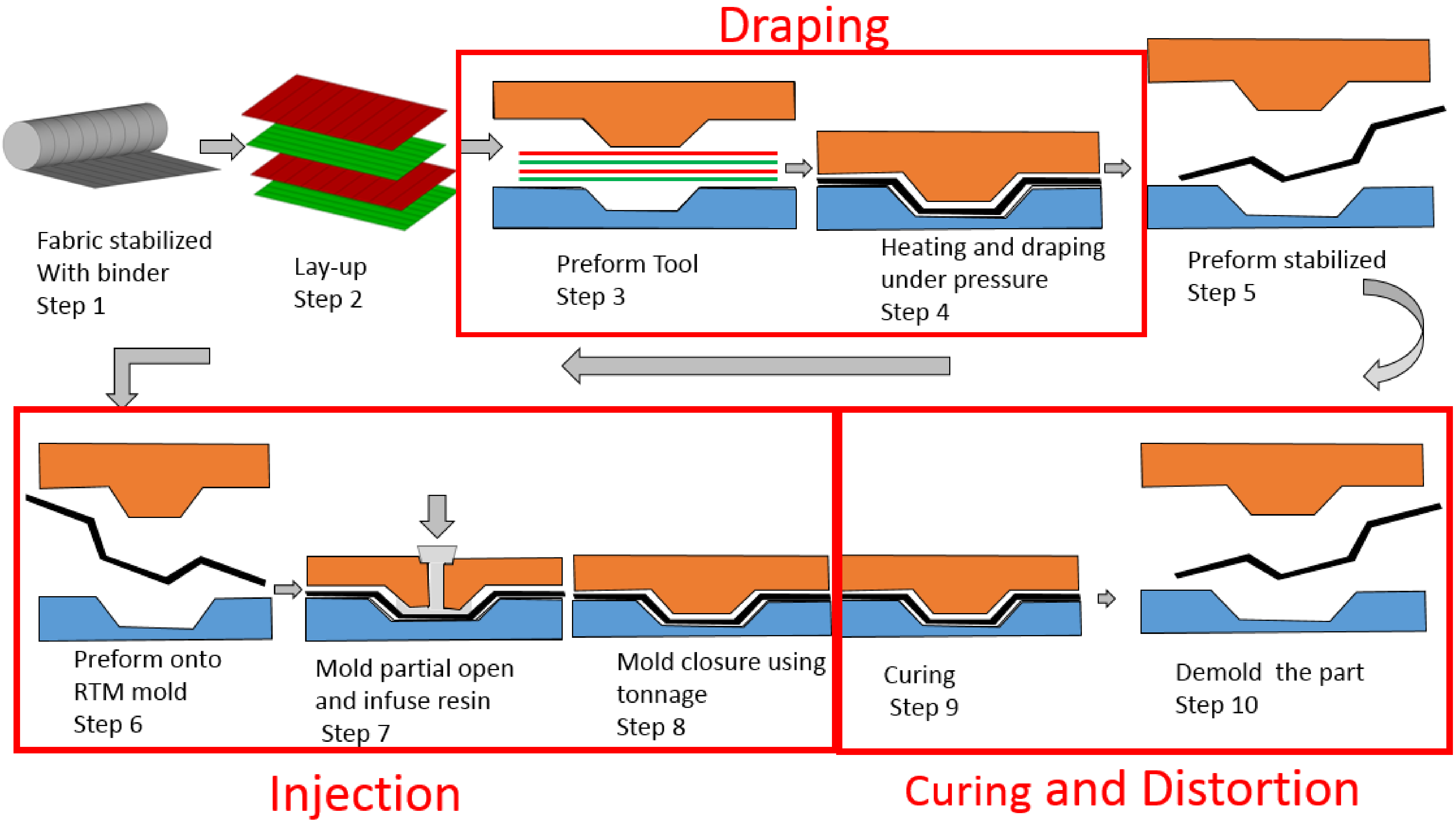
Patents

- A total of 7 patents submitted to Government Patent office.

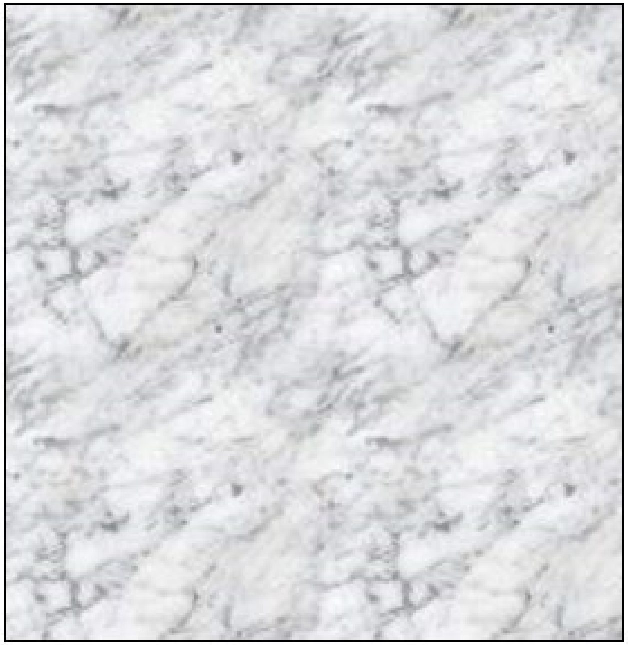
Facilities

- GM commissioned an HP-RTM system to facilitate the molding for the project. One assembly component will be molded at GM.
- CSP moved their HP-RTM equipment from France to CSP HQ in MI, USA. Three components of the assembly will be molded at the CSP facility.

Manufacturing Process

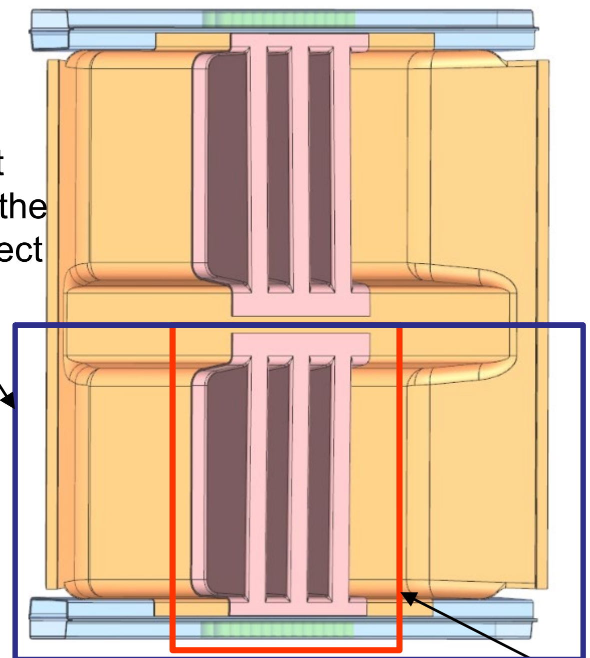


Demonstration/Validation of Computational Tools



Light Weight Underbody Ultra High Strength Steel Assembly

Built
For the
project



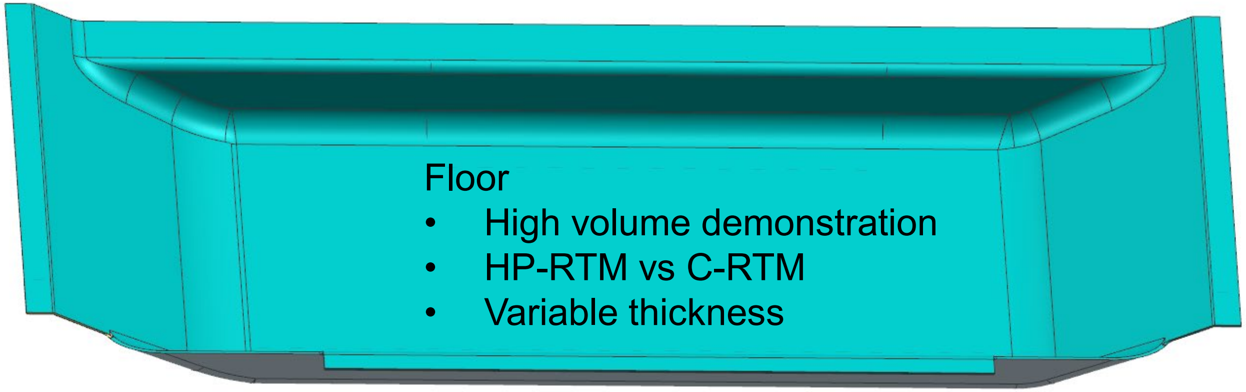
Replacement Carbon Fiber Assembly

Portion of the assembly built for the prototype evaluation

- Significant parts consolidation - more than 60 steel parts to 9 composite parts
- Carbon fiber design is 30% lighter than steel
- Further optimization is expected to improve the weight savings to ~ 40%

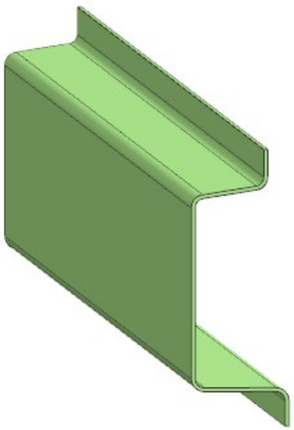
Objectives:
a) Demonstrate the HP-RTM technology for high volume manufacturing
b) Compare the side pole impact performance of carbon fiber with baseline steel by testing
c) Evaluate the weight savings and cost increase per pound saved

Carbon Fiber Parts – Underbody Assembly

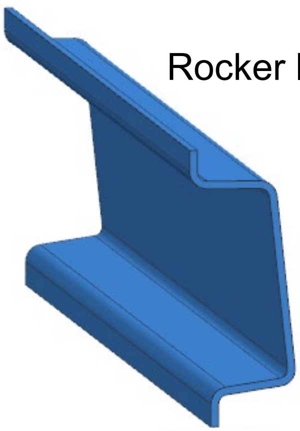


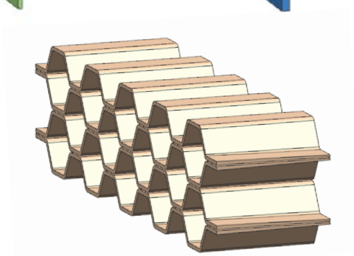
Floor
- High volume demonstration
- HP-RTM vs C-RTM
- Variable thickness

Rocker outer

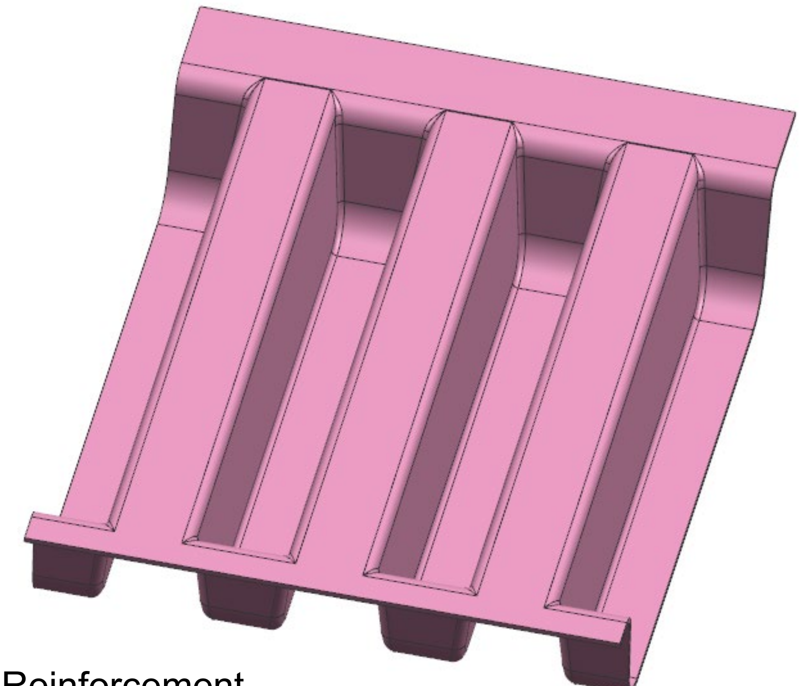


Rocker Inner



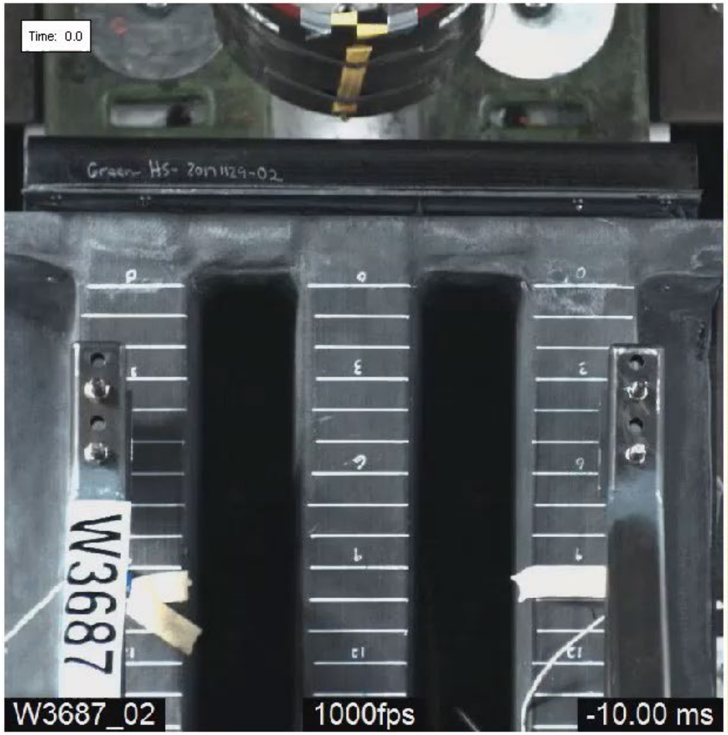


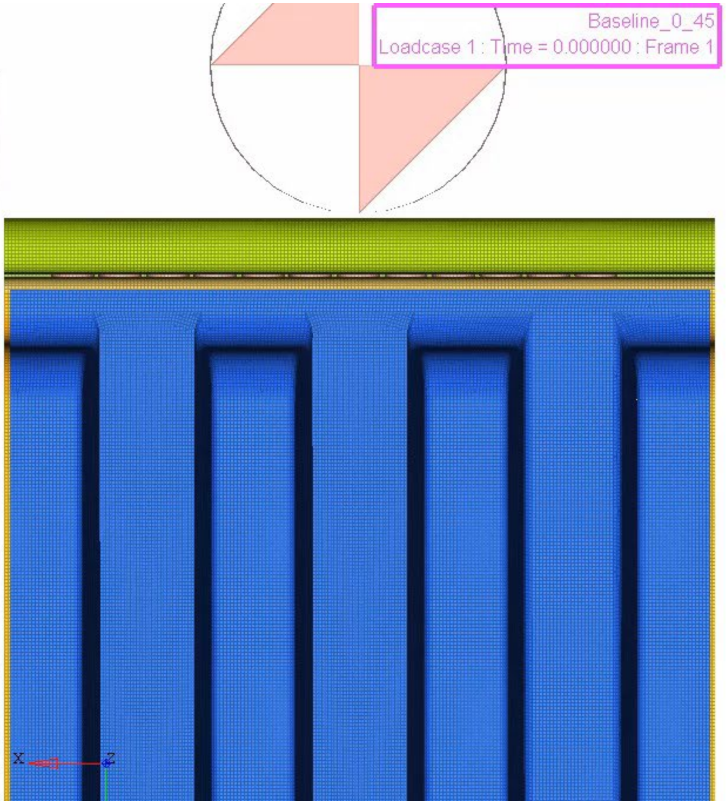
Thermoplastic
Energy absorber



Reinforcement
- Draping challenge due to complex geometry
- Slits for manufacturing effect the performance

Prototype Evaluation





Experiment

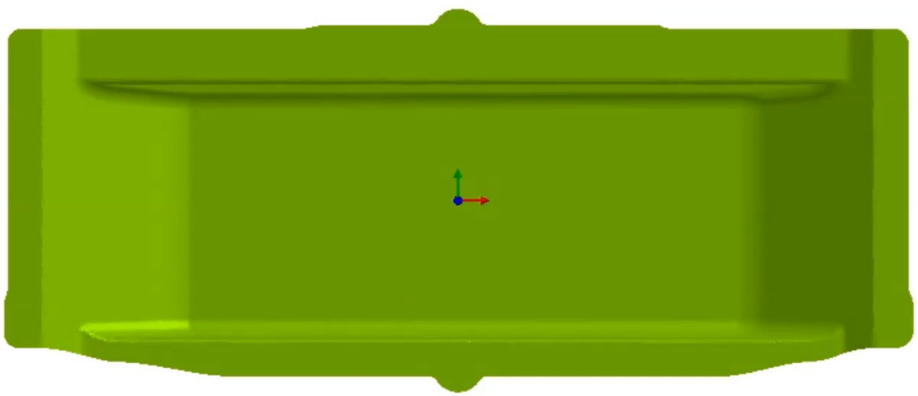
Simulation

During the testing, circular tubes used as an energy absorbers escaped from the rocker openings and damage was little more than the simulation – Damage locations matched.

Intrusion is only 2” and simulation correlated very closely!

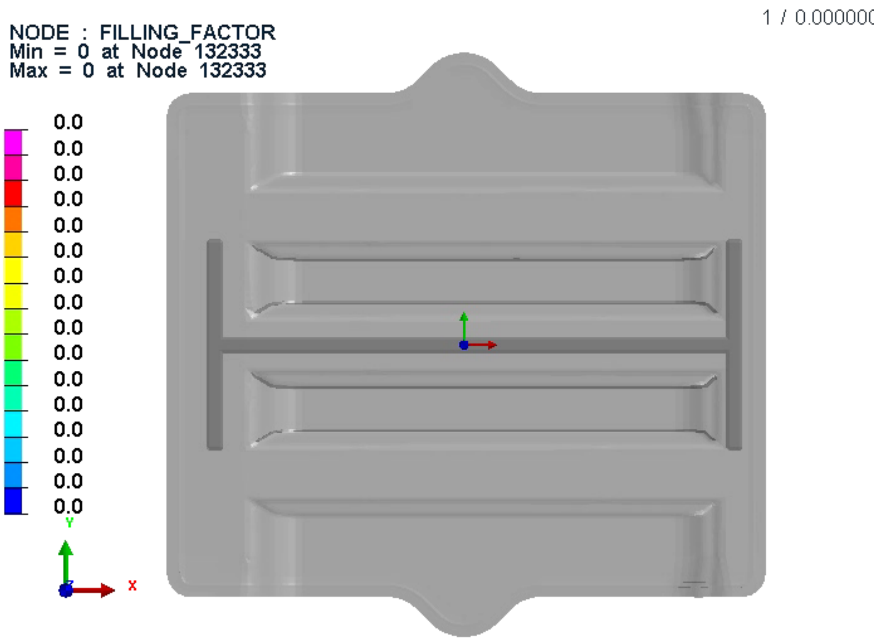
The design has greater applicability for Electric Vehicles!

Manufacturing simulation tool development and validation

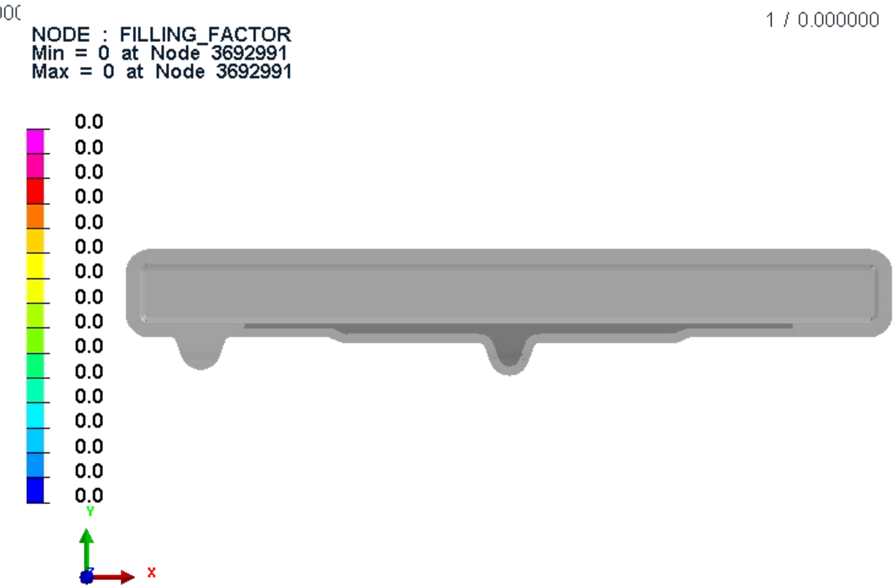


- Models developed and validated for a fast curing resin (coupling between fluid mechanics, heat transfer, polymer curing, and solid mechanics.)
- Tools design was engineered using 100% virtual simulation.
- Investing more than $1M on the tool design/build/mold for demonstration!

Manufacturing simulation tool development and validation

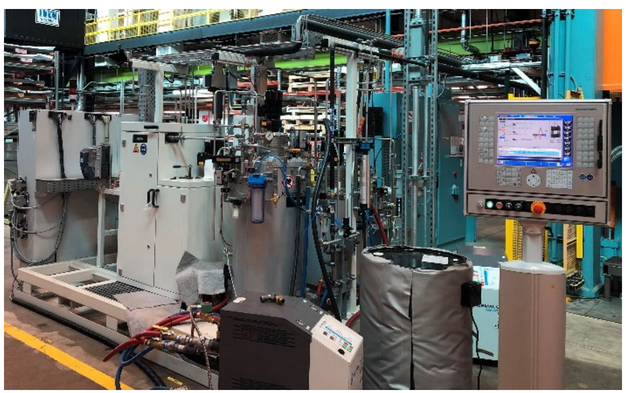


Reinforcement



Rocker Inner

Components to make 30-35 underbody assemblies will be molded using HP-RTM. Variability, cycle time, and throughput will be studied for each part as part of certification.



GM and CSP commissioned the HP-RTM systems in time to support the project

We believe this technology need to be explored to fullest potential to bring significant value to the composite industry

GM HP-RTM System

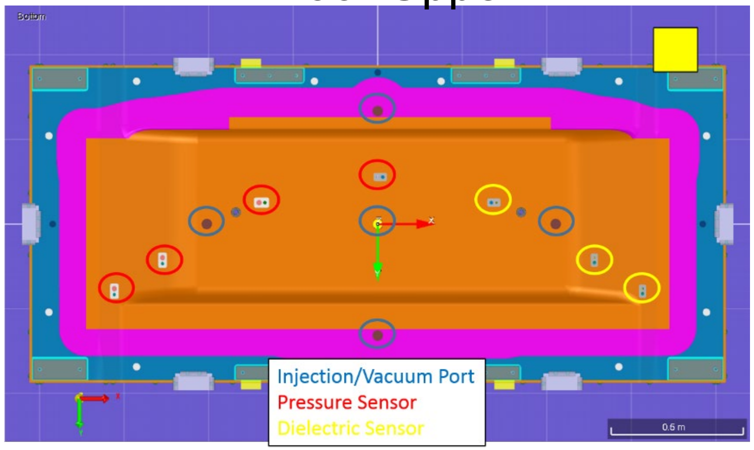
- 1000T Williams White press
- Krauss- Maffei injection system

CSP HP-RTM System

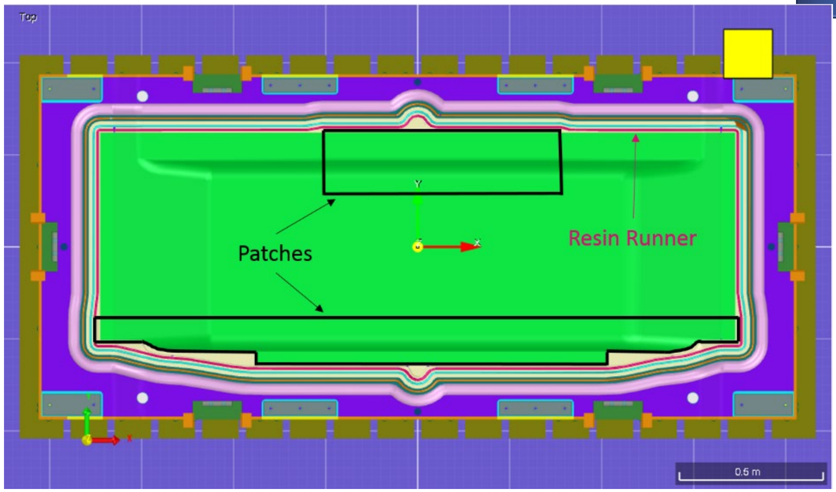
- 4000T Williams White press
- Custom made injection unit

Design and Build Tools for the Underbody Assembly

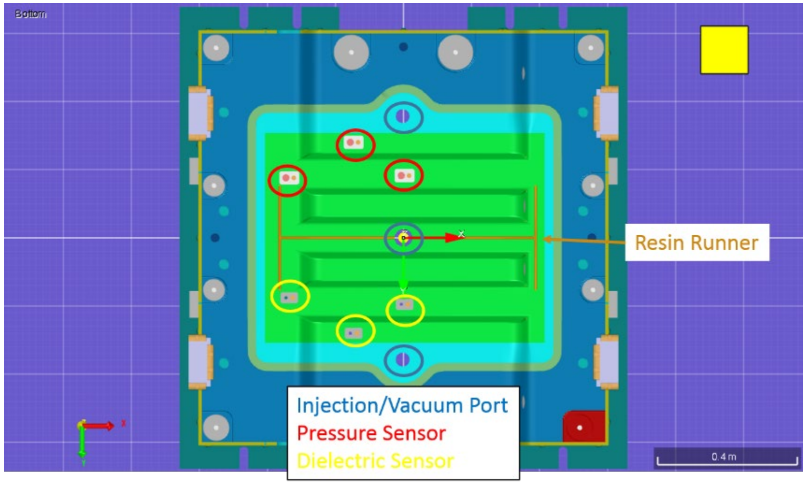
Floor Upper



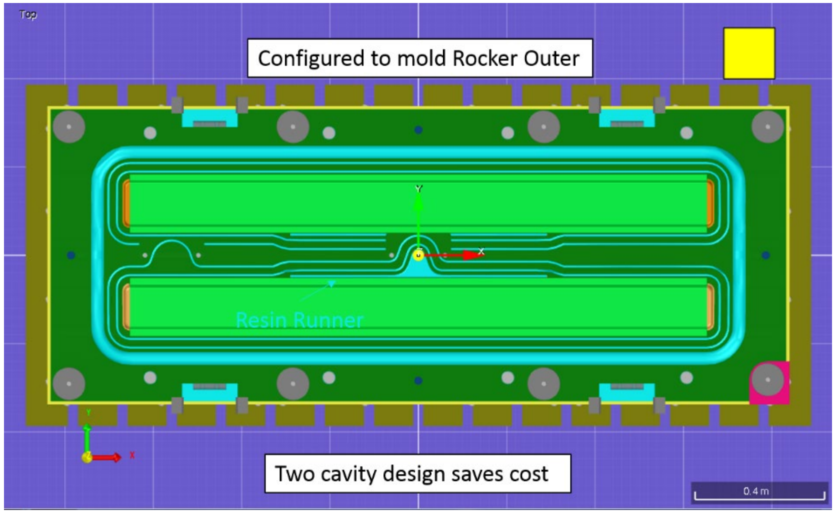
Floor Lower



Reinforcement Upper



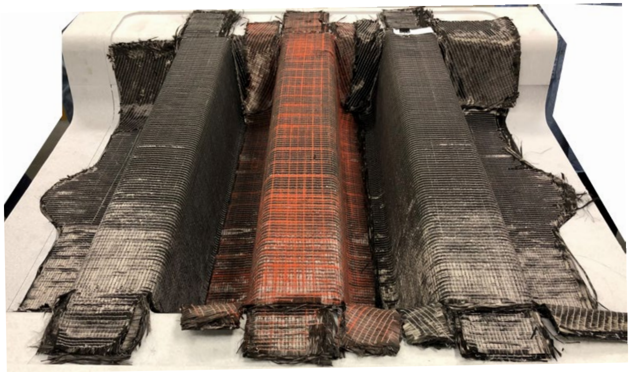
Rocker outer and inner



Pressure and Dielectric sensors were incorporated to collect the data and compare with model predictions.

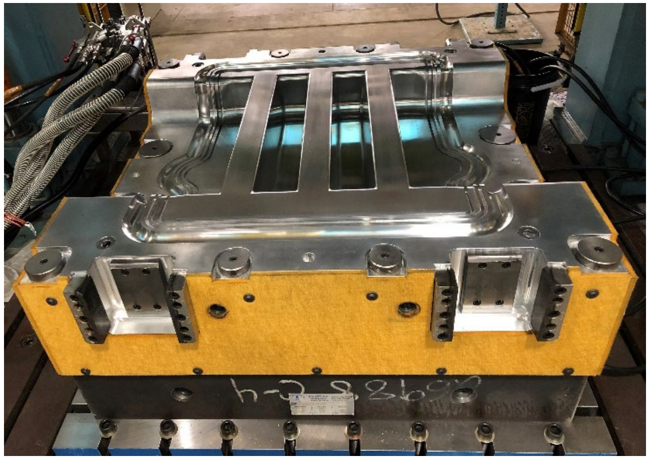
Three phases of molding – learnings from one phase are transferred to next phase

Fabrication of Components – Phase 1

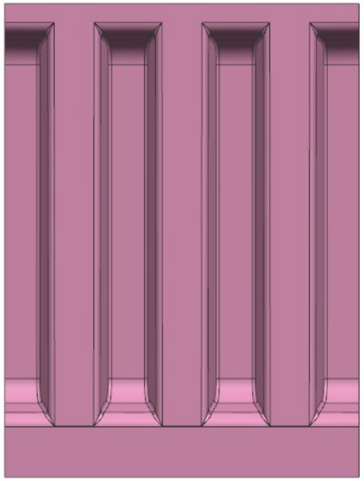


Pattern 1

Pattern 2 overlaid on preform 1

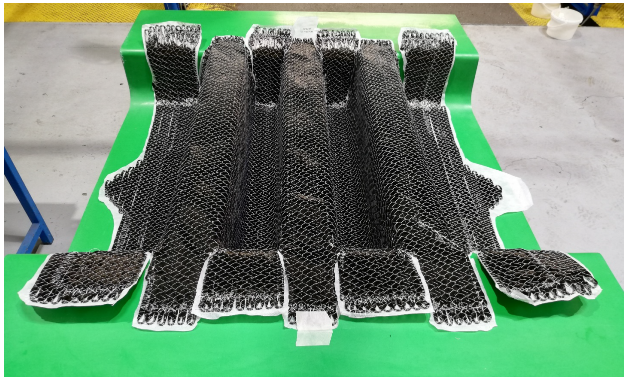


Reinforcement tool



Part Geometry

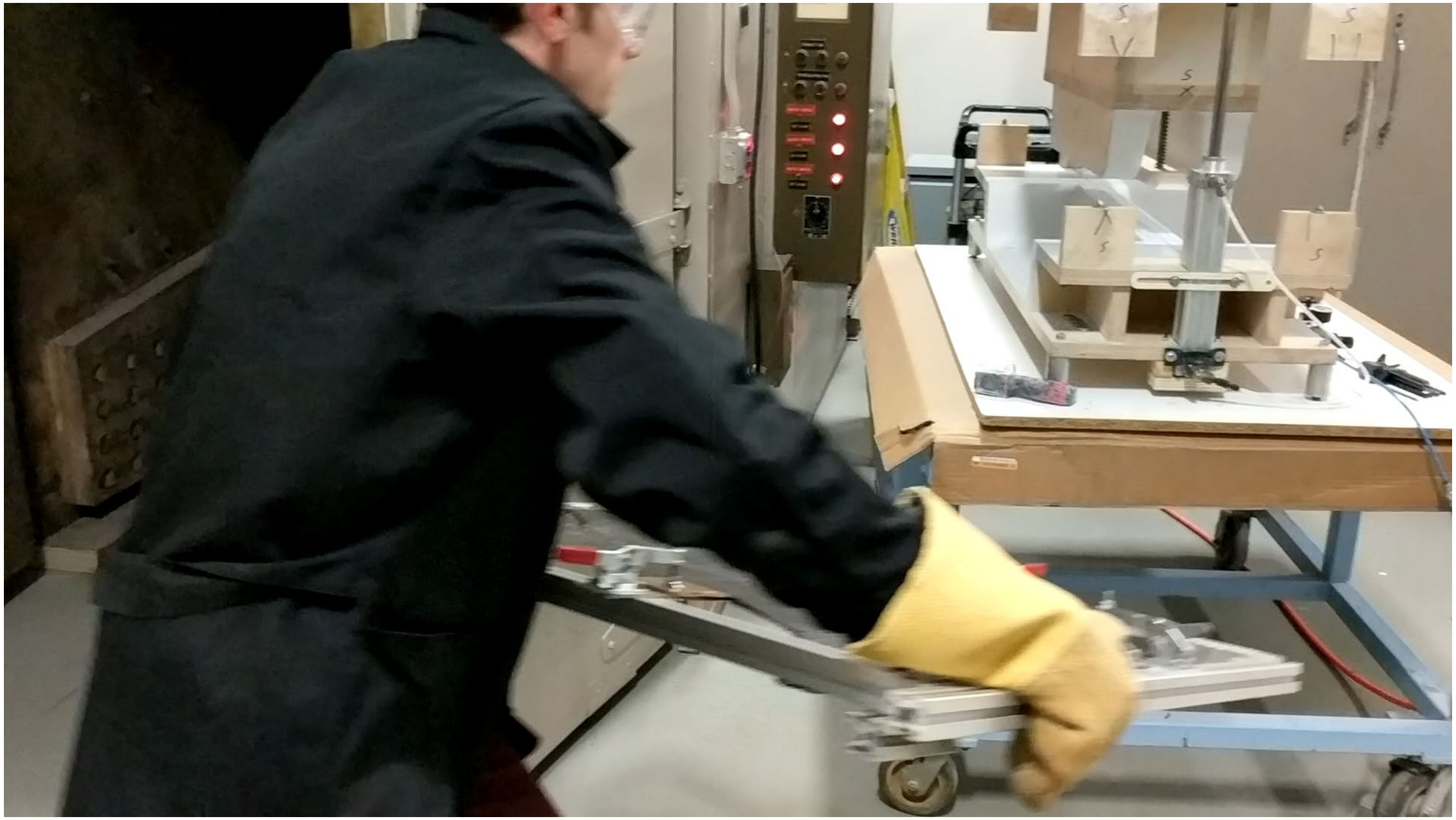
Lattice one piece preform



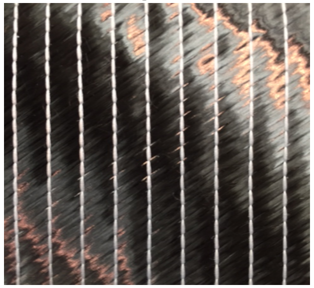
One step preform

- Non-crimp fabrics for optimum performance and cost – challenging for modeling!
- Simulations will give preform patterns for draping. Draping results will be correlated.
- Simulations drive molding conditions and experimental measurements will be compared.

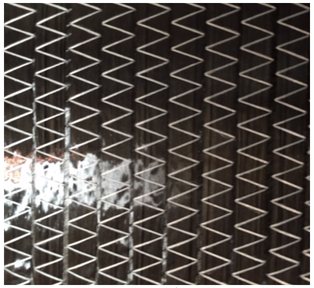
Preforming Fixture



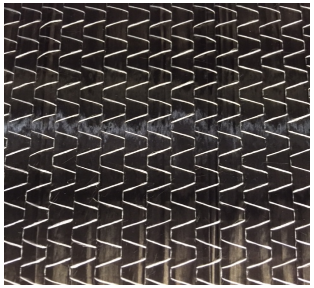
Different type of fabric types



chain



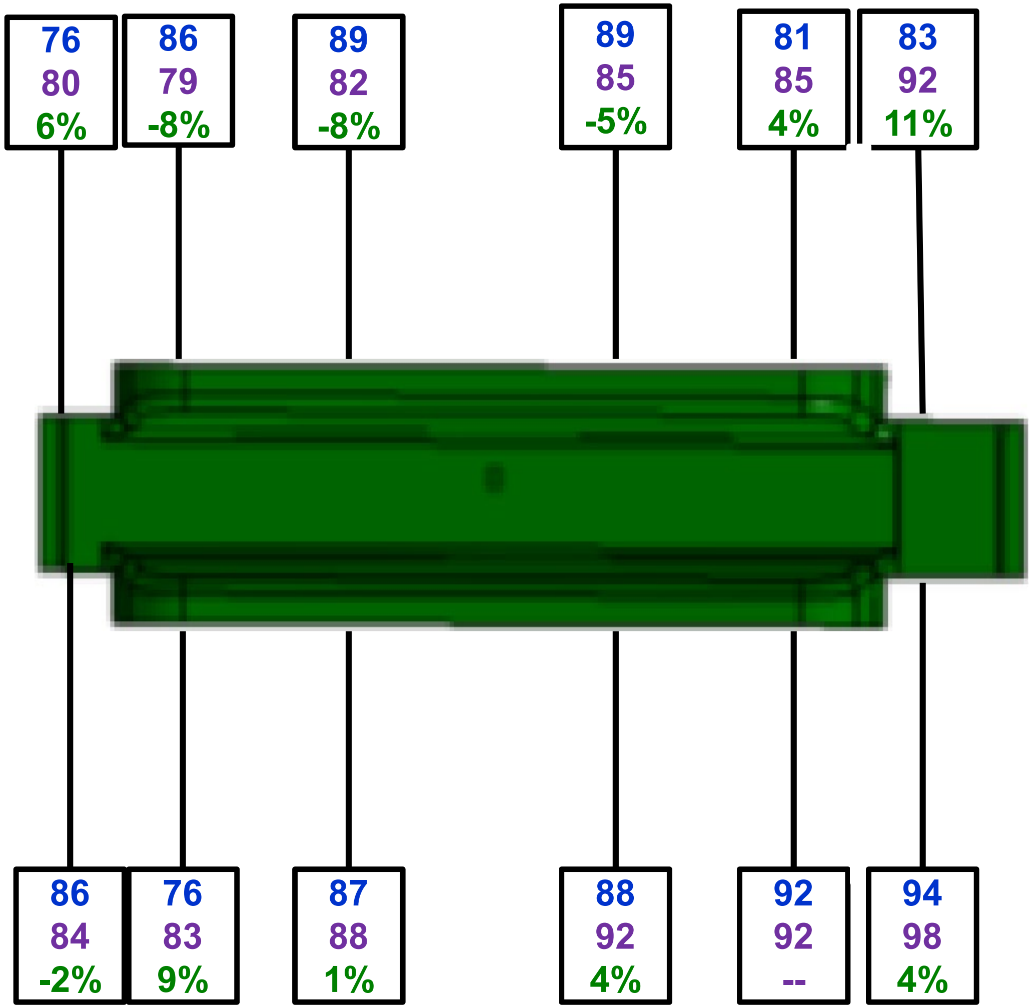
Tricot



Hybrid (combination of chain and tricot)

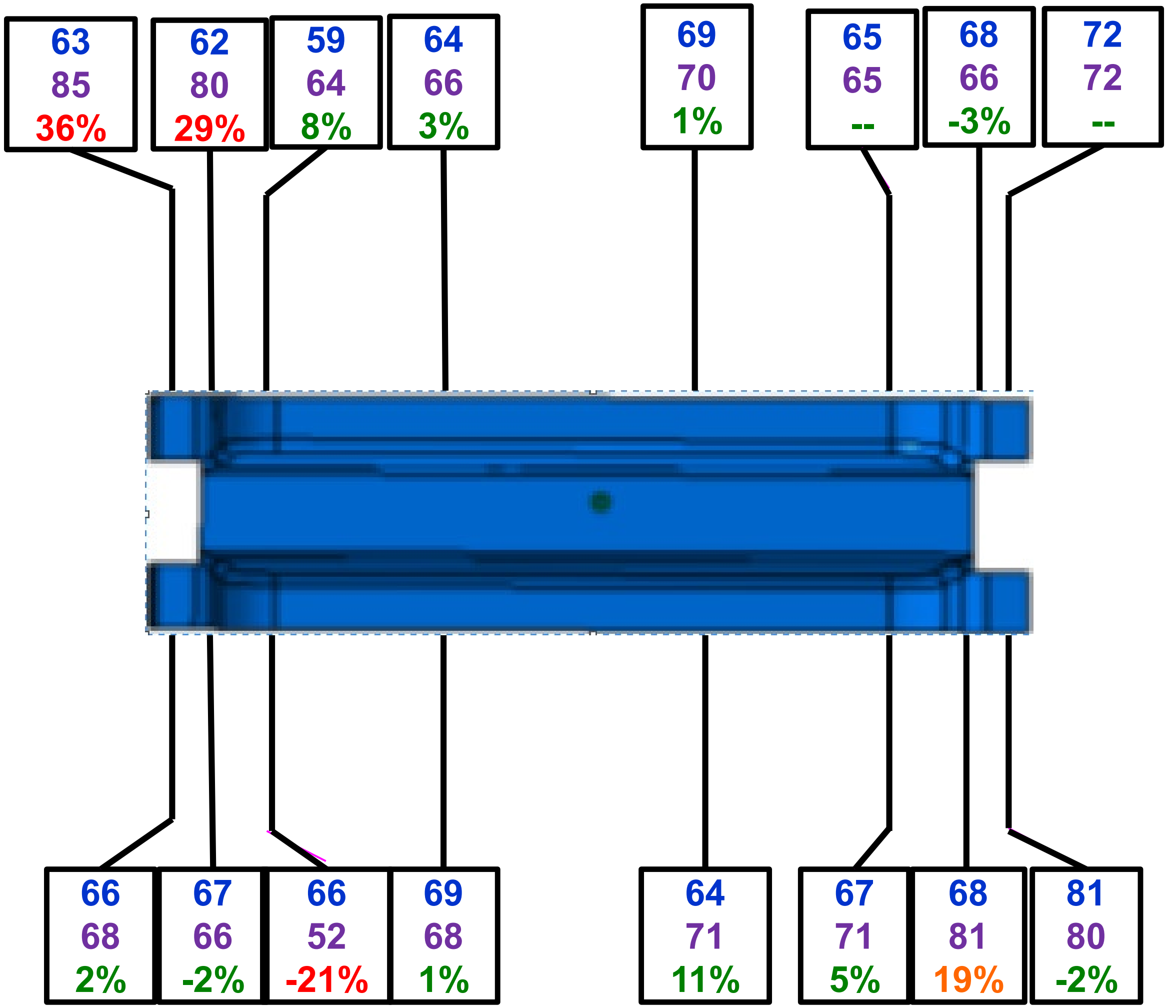
- A preforming fixture made of wood was designed and built to help in computational tool development for modeling the draping behavior of non-crimp fabrics.
- It will be also used to make preforms for the molding the reinforcement for the assembly

Draping Comparison
Experimental to Simulation



83 – Experimental Value
92 – Simulation Value
11% - Difference Simulation to Experimental

Draping Comparison Experimental to Simulation



63 – Experimental Value
85 – Simulation Value
36% - Difference Simulation to Experimental

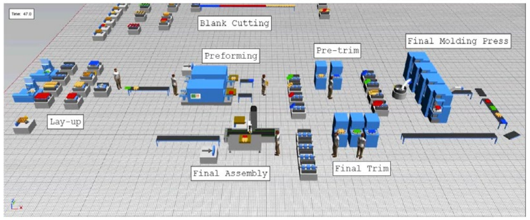
Cost Modeling for HP-RTM

Crucial data from process simulation

+

Empirical + Experience

=



- Process steps
- Preform size
- Cycle time
- Press selection

- Die cost based on volume
- Automation
- Floor space
- % of scrap
- downtime
- Press allocation
- maintenance

Current Project - Technology Impact Areas

Materials

- Low cost NCF
- Tow size effects (different numbers of fibers)
- Use of long fiber thermoplastic composite for energy absorption
- Stochastics at the micro-scale

Process

- Draping
- HP-RTM/C-RTM, process monitoring, and optimization
- Fast curing resins

Structure

- Multi-scale
- Manufacturing effects
- Nonlinear plasticity

Performance

- Integrated performance
- Stochastic performance
- Non-orthogonal weaves
- Crashworthiness

Responses to Previous Year Reviewers' Comments

1. The reviewer asked about the specific component to demonstrate the approach.

Answer: For the demonstration, we have selected to redesign a best in class ultra high strength underbody steel assembly. This assembly location was protected for GM for the project and it was not disclosed in earlier reviews.

2. The reviewer was not clear about the resources for the remaining work as he was of the opinion that the demonstration work will be undertaken in the last year.

Answer: The demonstration work started at the beginning of the project. As this item was a protected item for GM in the beginning, we could not mention in this open review. The baseline steel underbody assemblies were tested for resistance to side pole impact in the first year and the results will be used to correlate with the values from the carbon fiber assembly in the next few months. Resources are sufficient to complete the project with promised deliverables.

Partners/Collaborators

General Motors - Prime	Overall project management, execution, baseline performance evaluation, material data generation for manufacturing and structural simulations, assembly of the CF automotive assembly, testing and validation. material database creation for manufacturing and structural simulation, integrate the manufacturing and structural models, develop cost models, demonstrate the technology development.
Continental Structural Plastics (CSP)	Technology supplier, molder - coupons, plaques and components, develop design for manufacturing guidelines, input for cost models.
ESI Group, NA	Manufacturing simulation models for the manufacturing processes chosen in the project.
Altair	Multi-scale simulation models for the structural performance in the LS-DYNA, ABAQUS and Radioss framework.
University of Southern California	Develop stochastic drivers that work for manufacturing and structural performance simulations. Able to utilize the previous work done on a DOE supported work on uncertainty quantification (SciDAC institute).

Remaining Challenges and Barriers

(Any proposed future work is subject to change based on funding levels)

- Building the components for the underbody assemblies using HP-RTM and collection of all the important data.
- Comparing the predictions from the manufacturing simulations with the experimental results for validating the models.
- Crash testing the carbon fiber underbody assembly and comparing the experimental results with predictions. Also, comparing the results with the baseline steel assembly.
- Completing the cost models to evaluate the cost increase per pound saved for evaluating the business case.

Proposed Future Research

(Any proposed future work is subject to change based on funding levels)

FY 2019

- Fabricate and assemble the components of the underbody assembly.
- Evaluate the assembled component in side pole impact.
- Collect the experimental data for the manufacturing (HP-RTM/C-RTM) and structural performance (crush load, damage), etc. stochastically.
- Validation of the ICME tool - Comparison of the prediction with the experimental results for manufacturing and structural performance.

Summary

- A large automotive underbody assembly was designed virtually for use with carbon fiber composites.
- Tooling to manufacture the desired parts were fabricated.
- Four major components were molded using both HP-RTM and C-RTM.
- A prototype assembly was built with low cost tools to validate the design. Test results showed that design was a success; providing greater confidence for the HP-RTM tool build.
- Cost models were developed to understand future potential research areas for cost reductions.

Thank You!

Technical Back-Up Slides

Governing Equations in Injection, Curing and Warpage

Filling – Stage – Coupled flow, heat and cure

Darcy's equation – Fluid Flow $\nabla \cdot (-\frac{K}{\mu}\overrightarrow{\nabla P}) = 0$

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

Curing Kinetics $\frac{d\alpha}{dt} = (A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m) \cdot (B - \alpha)^n$

Curing – Stage – Coupled heat and cure

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

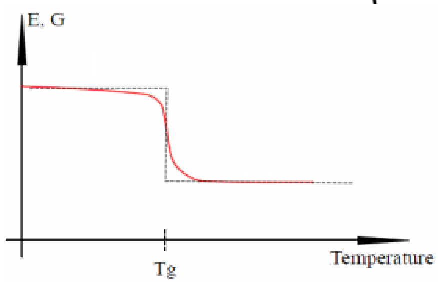
Curing Kinetics $\frac{d\alpha}{dt} = (A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m) \cdot (B - \alpha)^n$

Distortion- Stage (Thermo- Chemical Mechanical Analysis)

$$\sigma_{ij}(t) = \int_0^t C_{ijkl}\big(\xi(t) - \xi(\tau)\big) \frac{\partial\left(\epsilon_{kl} - \epsilon_{kl}^E\right)}{\partial \tau} d\tau \qquad C_{ijkl}(t) = \begin{cases} 0 & , X < X_{gel} \\ C_{ijkl}^{\infty} + \sum_{p=1}^{P} C_{ijkl}^{p} \cdot \left(e^{-t/\rho_{ijkl}^{P}}\right), X \geq X_{gel} & , \text{no sum on } i, j, k, \end{cases}$$

Di Benedetto function → T_g

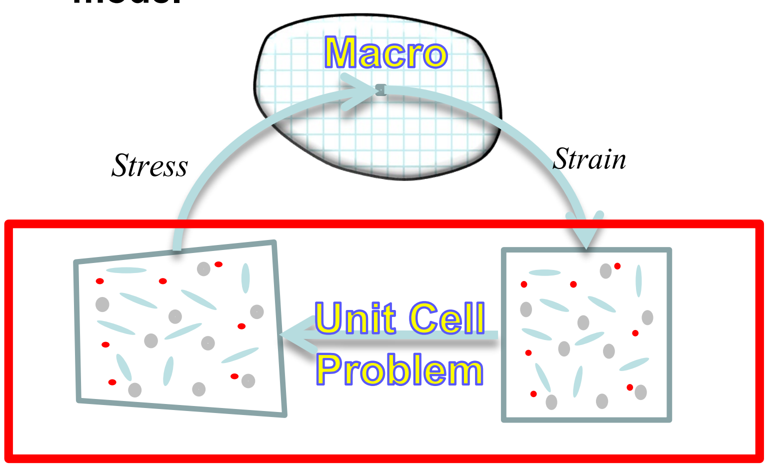
$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda X}{1 - (1 - \lambda)X}$$



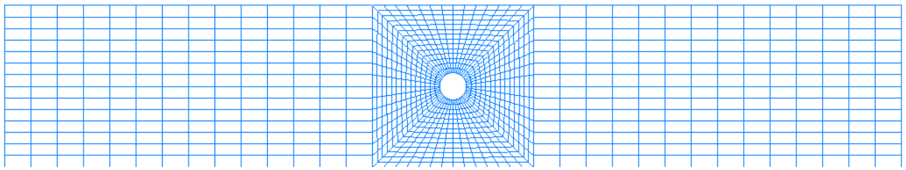
Multiscale Designer Capabilities

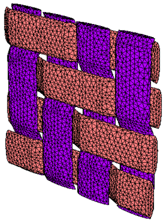
1. Parametric RVE definition
    1) Geometric scripts
    2) User-defined parametric RVE
    3) Integration with experimental data

2. Computational Efficiency: **Speed comparable to single scale model**



3. Size Effect & Softening after Damage





Challenges:
(1) Unit cell size comparable to the hole size and much bigger than macro-element size
(2) Strain softening due to damage

An attempt to account for size effect and softening due to damage

Remedies:
(1) Rescaling of damage models and
(2) Staggered nonlocal multiscale approach